

JPL Cryocooler Development and Test Program: A 10-year Overview

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Abstract—In the 1988 timeframe increasing numbers of proposed space-instrument programs within NASA and the Ballistic Missile Defense Organization (BMDO) were in need of high-reliability, long-life, low-vibration space cryocoolers. To ensure the success of its emerging cryogenic instrument commitments, the Jet Propulsion Laboratory (JPL) implemented a focused multi-year cryocooler program. Over the past 10 years the JPL cryocooler program has included the procurement/development of pulse tube cryocoolers for the AIRS, TES and IMAS JPL/NASA instruments, performed extensive characterization testing of 22 industry-developed cryocoolers, developed and flight-tested a wide variety of cryocooler integration technologies, and developed sorption cryocoolers for use at 10 to 25 K. An overview of the ten years of progress is presented together with a thorough bibliography of published documents describing the work.

INTRODUCTION

With the successful laboratory development of the Oxford University Stirling cryocooler in the late 1980s, several advanced space-instrument programs within NASA and BMDO began to baseline long-life, low-vibration space Stirling cryocoolers operating in the 30 to 150 K temperature range. Within NASA, seven science instruments selected for the Earth Observing System (EOS) program contained cryocoolers: AIRS, DLS, HIRRLS, MLS, SWIRLS, SAFIRE and TES. Later, MOPITT and ASTER (first known as TIGER) were added as EOS instruments using cryocoolers, DLS and HIRRLS were combined into a single instrument HIRDLS, and SAFIRE and SWIRLS were dropped.

Initial projections were for the delivery of three units of each instrument, thus requiring as many as 80 long-life space cryocoolers for the EOS program. Since four of these instruments (AIRS, MLS, SWIRLS and TES) were JPL instruments, JPL had a strong vested interest in the successful development and application of long-life space cryocoolers.

To ensure the success of its EOS cryogenic instrument commitments, JPL implemented a multi-year cryocooler program in 1988 to establish the needed technology and knowledge base [1,2]. Over the past 10 years the JPL cryocooler program has played a lead role in the procurement/development of cryocoolers for the AIRS and TES instruments, developed a next-generation pulse tube cryocooler for the IMAS instrument, conducted extensive characterization testing of 22 industry-developed pulse tube and Stirling coolers, developed

and flight-tested a wide variety of cryocooler integration technologies, and developed sorption cryocoolers for the 10 to 25 K temperature range. This paper provides a roadmap to the activities and developments of the JPL cryocooler program over the past ten years and provides a relatively complete bibliography of the publications that document the work. Because of the high level of commonality that has existed between the NASA and BMDO cooler requirements [3], the JPL program has been a highly collaborative, cooperative program involving funding from both NASA and BMDO and major contractual development efforts within the worldwide aerospace industry.

The JPL cryocooler program has been focused in four areas:

- 1) The fundamental focus of the JPL cryocooler program is supporting the development and cryogenic engineering of JPL instruments that require cryocoolers to meet their scientific objectives. This activity involves cryogenic instrument design, cryocooler definition, selection and procurement, cryocooler integration engineering, and extensive cryogenic system testing. Several JPL flight instruments involving cryocoolers are currently being supported. The largest are JPL's Atmospheric Infrared Sounder (AIRS) instrument and the Tropospheric Emission Spectrometer (TES) instrument.

- 2) To support the design of JPL's cryogenic instruments, a second principal focus has involved extensive characterization testing of industry-developed cryocoolers. This activity has been conducted to provide a thorough performance database for use by JPL and the broader NASA and DoD instrument development and cryocooler development communities. JPL initiated its cryocooler characterization program in support of the AIRS instrument in 1989, and greatly expanded the effort under the sponsorship of the Ballistic Missile Defense Organization (BMDO) and the Air Force Research Laboratory (AFRL) in 1992. Over the past several years, 22 different cryocooler models have been characterized.

- 3) The third element of JPL's cryocooler program involves conducting research to develop cryocooler integration technologies needed to enhance the successful incorporation of cryocoolers into space instruments. Example cooler integration technologies include heat switches, heat interceptors, and closed-loop vibration suppression systems. A valuable part of this activity has been the carrying out of selective flight experiments to provide flight heritage data and insure that no unresolved issues exist with respect to meeting the complete end-to-end development cycle of flight hardware.

4) The fourth element of JPL's cryocooler program involves conducting research and development of advanced vibration-free sorption refrigerators for operation in the range of 10 to 25 K. An important accomplishment in this area has been the successful development of JPL's Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE), which was successfully operated aboard STS 66 in 1996.

These JPL cryocooler programs are summarized below and described in detail in the cited references. For ease of presentation, the activities are grouped according to operating temperature, starting with 30 to 130 K mechanical cryocooler activities, and ending with 10 to 25 K sorption cooler activities.

30 TO 130 K FLIGHT INSTRUMENT CRYO-ENGINEERING

As noted above, the fundamental focus of the JPL cryocooler program is supporting the development and cryogenic engineering of JPL space instruments that require cryocoolers to meet their scientific objectives. This activity involves cryogenic instrument design, cryocooler definition, selection and procurement, cryocooler integration engineering, and cryocooler system testing. JPL's two largest flight instruments involving cryocoolers are AIRS and TES.

AIRS Cryocooler Development

One of the leading NASA applications for advanced space cryocoolers is JPL's Atmospheric Infrared Sounder (AIRS) instrument (Fig. 1). This instrument is an atmospheric air temperature measuring instrument scheduled to be flown on NASA's Earth Observing System PM platform in the 2000 timeframe; it is being designed and built under JPL contract by Lockheed Martin Infrared Imaging Systems, Inc. (LMIRIS) of Lexington, MA. The cryocooler development effort is a highly collaborative effort involving cryocooler development at TRW, and extensive cryocooler testing at JPL and Lockheed Martin [4]. In the first phases of the AIRS cooler effort, contracts were awarded to BAe (now MMS) and Lockheed-Lucas for the development-testing of advanced second-generation Stirling cryocoolers with the needed capacity, efficiency, and low vibration. These early efforts fostered important design improvements associated with reduced off-state conduction down the cold finger, and high accuracy coldtip temperature regulation via compressor piston stroke control [5,6]. They also illuminated important technical chal-

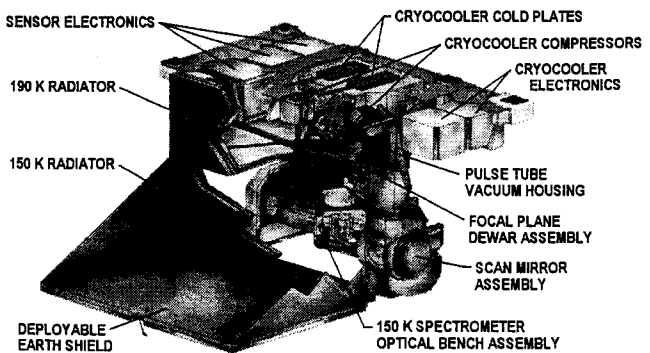


Figure 1. Operational elements of the overall AIRS instrument

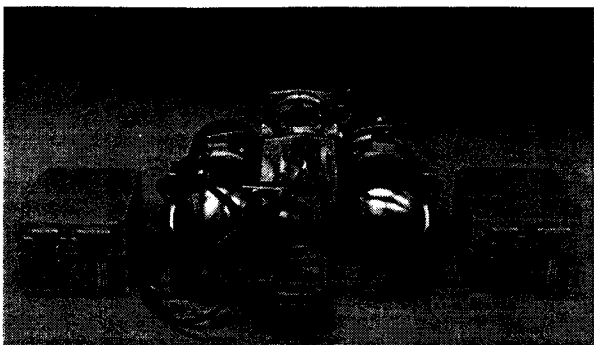


Figure 2. AIRS flight cryocoolers and drive electronics

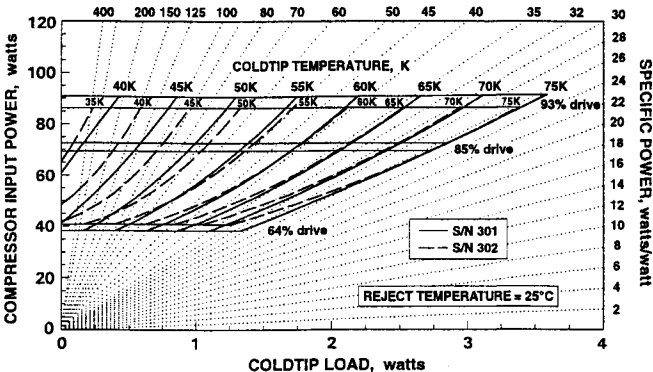


Figure 3. Measured thermal performance of the AIRS flight pulse tube coolers in terms of compressor input power with 25°C heat rejection coldplate temperature.

lenges that could be more easily met by the use of an advanced pulse tube expander in place of the Stirling displacer.

In 1994, LMIRIS awarded TRW the contract to develop and produce the flight coolers for the AIRS instrument. The TRW AIRS pulse tube cooler, shown in Fig. 2 with its drive electronics, has excellent thermal performance, comparable to the best Stirling coolers, and has a number of features that greatly improve instrument integration. These include reduced mass, size and complexity, increased stiffness, and reduced vibration at the cold head. Figure 3 summarizes the thermal performance of the AIRS cooler, which was designed for a nominal 1.5 watt load at 55 K; Table 1 summarizes the mass breakdown of its principal components. The AIRS flight pulse tube coolers, delivered to JPL for testing in October 1997, and to LMIRIS for instrument integration in January 1998, have been extensively characterized and have met all of their key performance goals [7,8].

Table 1. Breakdown of mass of AIRS cryocooler system.

ITEM	Mass (kg)
Total cryocooler S/N 301 (primary) weight	13.4
Compressor	7.88
Pulsetube expander	0.27
Electronics	4.62
Compressor-to-electronics cables	0.63
Total cryocooler S/N 302 (backup) weight	13.4
Pulsetube vacuum housing and heat sinks	3.6
Integrating structure/coldplate support	5.1
Compressor magnetic shields	1.5
Total cryocooler assembly	37.0

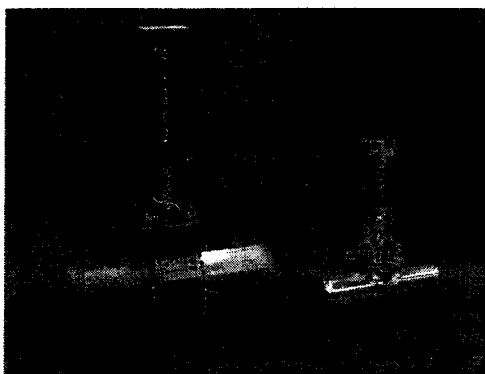


Figure 4. TES pulse tube cryocooler (left) in comparison with the new IMAS pulse tube cryocooler (right)

TES Cooler Development

The second large cryogenic instrument presently under development at JPL is the EOS Tropospheric Emission Spectrometer (TES) instrument. TES is an infrared satellite instrument designed to measure the state of the earth's troposphere. It is scheduled for launch into polar orbit aboard NASA's third earth observing systems spacecraft (EOS-CHEM) in December 2002.

TES uses two coolers to cool two separate focal planes to 57 K. The two coolers are identical and are a variant of the TRW AIRS pulse tube cooler, but configured with the pulse tube hard mounted to the compressor (Fig. 4). The coolers are being fabricated by TRW under contract to JPL, and are scheduled for delivery to JPL for testing and instrument integration in 1999.

IMAS Cooler Development

A third JPL instrument requiring cryogenic cooling is the Integrated Multispectral Atmospheric Sounder, a proposed follow-on instrument to AIRS. The goal of the IMAS instrument was to provide a future option for performing the AIRS atmospheric air temperature sounding with a significantly smaller, lighter and more power efficient instrument. To support this objective a development program was carried out with TRW in the 1996-1998 timeframe to achieve a radically smaller, lighter and more power efficient cooler, referred to as the IMAS cooler. This very successful development effort led to a new cooler with comparable thermal performance to the AIRS and TES coolers, but with one quarter of the mass and size [9]. Figure 4 contrasts the IMAS cooler with the much larger TES cooler.

A second important part of the IMAS development effort focused on improving the cryocooler electronics. A key issue with nearly all previous coolers is the presence of large amounts of ripple current passed on to the spacecraft's 28 Vdc power bus. On AIRS and TES this ripple current, shown in Fig. 5 for the two AIRS units, required the introduction of additional special ripple filters between the cryocooler and the spacecraft power system. For IMAS, an active ripple suppression circuit was developed and integrated directly into the cryocooler drive electronics with minimal efficiency and mass penalty. The resulting ripple, around 6% p-p/ave, is easily accommodated by most S/C power systems.

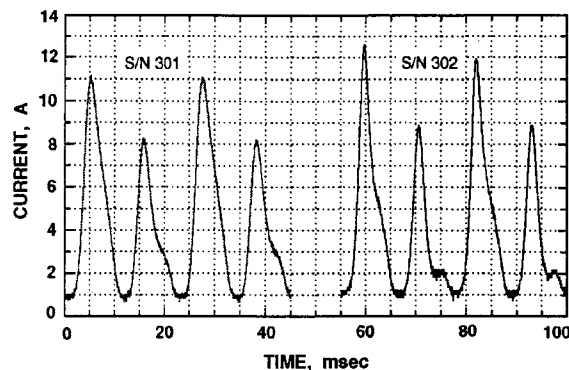


Figure 5. Comparison of the current waveforms on the 28 V power bus for the AIRS S/N 301 and 302 cryocoolers, each with a system input power of 110 W.

STIRLING AND PULSE TUBE CRYOCOOLER CHARACTERIZATION

In 1989, JPL initiated an extensive cryocooler characterization program to provide the foundation of cryocooler performance data needed for JPL's Atmospheric Infrared Sounder (AIRS) instrument and other JPL instruments requiring advanced, long-life, low-vibration cryocoolers [10]. The first cooler extensively characterized at JPL was the British Aerospace (BAe) 80 K "Oxford" cooler that JPL purchased in 1989; this cooler (Fig. 6) has served as the design basis of most long-life space cryocoolers and has served as a pathfinder for the development of many of the test facilities and test methods used at JPL today; a wealth of data has been generated on the robust performance of this cooler.

The JPL cryocooler characterization program was greatly expanded in 1992 under the sponsorship of the Ballistic Missile Defense Organization/Air Force Research Laboratory in collaboration with the AIRS project [11]. The objective of the expanded test program was to gather data covering all aspects of cooler performance affecting instrument compatibility including thermodynamic cooling capacity, cold finger off-state parasitics, location and amount of rejected heat, generated vibration, EMI, and launch survivability. Direct

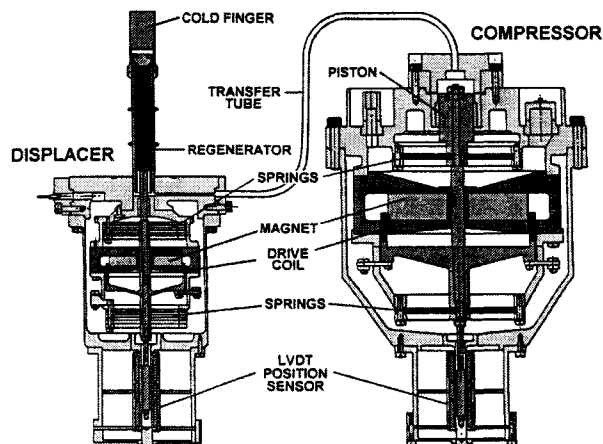


Figure 6. Cross-section showing the internal construction features of the Oxford 80 K cooler that have become the basis of most long-life space cryocoolers

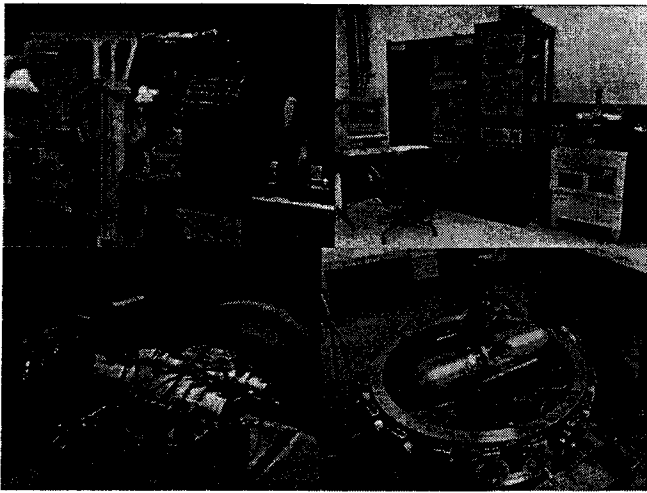


Figure 7. JPL cryocooler characterization test facilities

comparison of cooler characteristics was enabled through the use of a common set of instrumentation, test procedures, and test facilities. The JPL cryocooler characterization test facilities (Fig. 7) have grown to include many special-purpose test setups and data acquisition methods. Standardized test-result formats and parameter ranges are used to aid comparison and interpretation of cryocooler performance.

Since the characterization of the BAe 80 K cooler, 21 additional state-of-the-art cryocoolers have been characterized under the joint SDIO/BMDO/AIRS sponsorship. Six of these coolers have been less extensively tested to provide data for particular applications; these partially-characterized coolers include the Lockheed-Lucas 1710C Stirling cooler, the Hughes ISSC#4, PSC and SBIRS-low Stirling coolers, the TRW 0.25-watt 65 K mini-Stirling cooler, and the Magnavox MX7049 tactical Stirling cooler.

Comprehensive databases have been developed for the following 16 coolers:

- British Aerospace 80 K cooler [10-16]
- British Aerospace 55 K cooler [17]
- British Aerospace 50-80 K Cooler [18]
- Hughes 65 K SSC cooler
- Hughes 7044H tactical cooler
- Lockheed SCRS cooler
- Stirling Technology Co. 80 K cooler [19]
- Sunpower 140 K cooler [20,21]
- Texas Instruments 0.2 W-80 K tactical cooler
- Texas Instruments 1W-80 K tactical cooler [22]
- Texas Instrument 1.75 W-80 K tactical cooler
- TRW 1-watt 35 K pulse tube cooler [23,24]
- TRW 3503 pulse tube cooler [25,26]
- TRW 6020 pulse tube cooler [26]
- TRW AIRS pulse tube cooler [7,8]
- TRW IMAS pulse tube cooler [9]

In addition to the above referenced JPL papers that are focused on one particular cryocooler, summary overview papers have also been written to provide the user community with generic design data suitable for preliminary design purposes, prior to the selection of a particular cooler. These papers, which describe generic performance trends of present-day space cryocoolers, include thermal performance trends

[27], generated vibration trends [28], piston drive resonance characteristics [29,30], EMI characteristics [31], and cryocooler thermal stability [32].

Cryocooler Life-Test Facility Development—As a fallout of the effort to generate cryocooler characterization facilities, JPL has also designed and fabricated comprehensive life-testing facilities [33] for use by the Air Force Research Laboratory. These facilities were designed to obtain quantitative reliability data on the long-term performance of space cryocoolers, and to identify any possible time-dependent degradation or wear-out failures.

CRYOCOOLER INTEGRATION TECHNOLOGY DEVELOPMENT

Because very few cryocoolers have flown in space, many unknowns exist relative to the demanding challenges associated with the integration of cryocoolers into space instruments. To help ferret out these unknowns, JPL has conducted a number of focused technology development efforts including critical flight experiments directed at key high-risk, high-payoff integration technologies.

NASA IN-STEP Cryo System Experiment

One of JPL's first cooler integration projects was the NASA IN-STEP Cryo System Experiment in the 1992 to 1994 timeframe. This flight experiment, managed by JPL and carried out by the Hughes Aircraft Co. (now Raytheon), involved the first flight of a long-life space cryocooler in the U.S. and the first flight of a U.S.-built long-life space cryocooler. The objective of the flight experiment was to validate and characterize the on-orbit performance of a hybrid cryogenic cooling system integrating two advanced cryogenic technologies: a state-of-the-art Hughes ISSC (Improved Standard Spacecraft Cryocooler) 65 K long-life, low-vibration Stirling cooler (Fig. 8), and a Hughes experimental diode oxygen heat pipe. The heat pipe enables large physical separation between the cryocooler and its thermal load, and provides on-off switching to limit reverse heat flow when the cooler is turned off. The ISSC Stirling cooler was developed by Hughes under AFPL/BMDO sponsorship and is the forerunner of their latest cooler being flown on SBIRS-low. The successful experiment, conducted aboard STS 63 in February 1995, led to a large number of valuable lessons on Stirling cooler system integration. Key issues included cryocooler heatsinking and control of loads during mechanical attachment to the cooler's coldfinger [34].

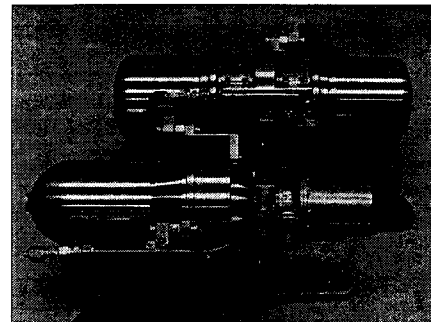


Figure 8. Hughes ISSC Space cryocooler flight tested aboard the CSE flight experiment on STS 63 in February 1995

Cryocooler Vibration Suppression Research

High levels of cooler generated vibration were identified early as an important issue relative to the application of cryocoolers to sensitive IR and gamma-ray instruments [13]. In an attempt to quantify and understand the nature of cryocooler vibration, JPL built the first cryocooler force dynamometer in 1990 [35]. This led to a multi-year program quantifying cryocooler vibration [28] and developing advanced vibration suppression algorithms for use internal to the cryocooler drive electronics. Advanced single-axis narrow-band vibration control systems were first developed under contract with SatCon Technology Corporation [36,37]. Then, advanced 3-axis vibration suppression systems were developed at JPL [38,39] and through a contract with the Massachusetts Institute of Technology [40].

STRV Cryocooler Vibration Flight Experiment

In the 1992 to 1994 timeframe, BMDO sponsored JPL to conduct a flight demonstration of the ability of an advanced control system to suppress cryocooler tip vibration in three axes [38,39]. The experiment (Fig. 9) was a small 15-watt payload aboard the Space Technology Research Vehicle (STRV-1b), a small English satellite that was launched on an Ariane-4 in June 1994. To meet the stringent power, weight, and space constraints, the experiment made use of the tiny 1/5-watt 80 K Texas Instruments tactical Stirling cooler. Motion of the coldfinger tip was measured in all three axes to 10 nanometer accuracy using eddy-current transducers, and the motion was controlled through the use of three piezo electric actuators. Two types of control systems were demonstrated: 1) an analog control system that used a bandpass filter to track the drive signal and suppress it, and 2) a digital narrow-band adaptive feed-forward system. The experiment was very successful and has operated in space for 4 years.

Cryocooler Heat Interceptor

In a proposal to take advantage of the presence of 140 K and 190 K cryogenic radiators in the AIRS instrument, JPL developed the concept of the heat interceptor. In this concept, a higher temperature cryogenic radiator is tied into the coldfinger of a Stirling or pulse tube cooler and used to intercept the cryocooler parasitic loads; the result is to nearly double the cryocooler efficiency. Under BMDO funding, JPL quantified the concept in detail [41,42] for the BAe 80K cooler. Although the heat interceptor was not used on AIRS, Raytheon

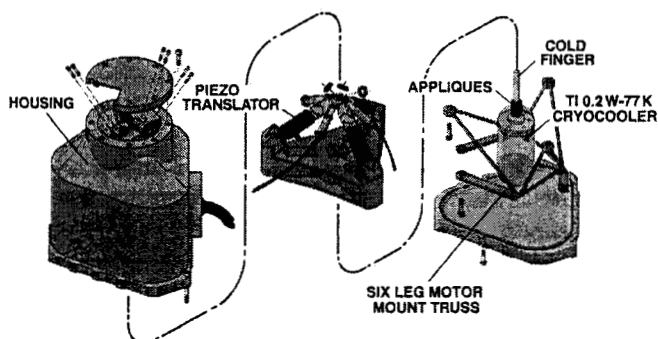


Figure 9. Construction features of JPL's STRV cryocooler vibration suppression experiment

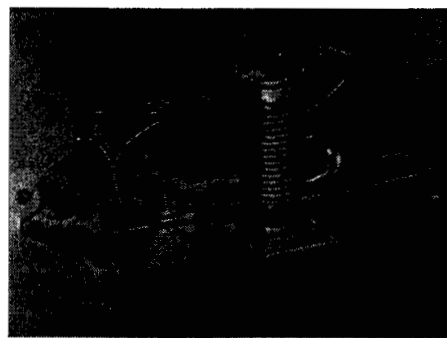


Figure 10. JPL developed gas-gap thermal switch

has incorporated the cryocooler heat interceptor concept into its 35 K coolers scheduled to fly on SBIRS-Low (formerly SMTS) in 1999 [43].

Cryogenic Heat Switch

Gas-gap thermal switches that allow selective coupling and decoupling of thermal loads is another integration technology developed at JPL for BMDO. Following earlier work on a switch for use at 10 K [44], more recent work has focused on temperatures in the popular 50 to 80 K range. In 1995 an advanced sorption-based gas-gap switch was developed for BMDO for use on the then Brilliant Eyes mission. Shown in Fig. 10, the switch has been recently upgraded for flight by Swales Inc., and was tested in space aboard the Space Shuttle STS 95 in October 1998.

STRV-1d QWIP Camera Experiment

The Space Technology Research Vehicle (STRV-1d) Quantum Well Infrared Photodetector (QWIP) camera experiment is a flight demonstration for BMDO designed to look at the suitability, maturity, and robustness of JPL-developed QWIP detectors as a viable alternative to HgCdTe detectors for LWIR applications. The flight experiment, scheduled to launch in 1999, is designed to look at the detectivity (D^*), uniformity, and radiation tolerance of the QWIP detectors. The detector is mounted directly to the 55 K coldfinger of a Texas Instruments 1-watt tactical cooler (Fig. 11) using an integral dewar assembly (IDA). Extensive ground testing has been performed to fully characterize the cooler over an extended range of heatsink temperatures and loads [22], and with the cooler operating with a flight-like battery pack, DC-DC converter, and cooler drive electronics. Test objectives include determining cooler/battery compatibility and measuring power train efficiency, inrush current levels, and current ripple.

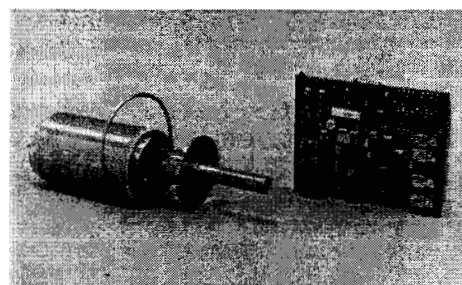


Figure 11. TI 1-watt cooler and drive electronics used to cool the QWIP detector on STRV-1d

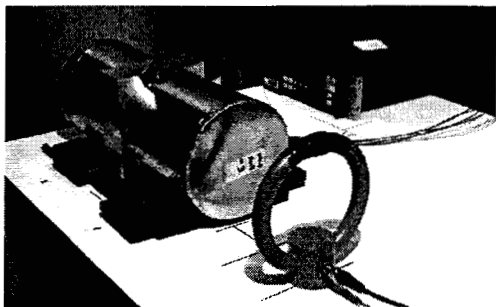


Figure 12. Magnetic shielding studies used this "magnetic mock-up" of the AIRS compressor with various shield materials, thicknesses and configurations.

Magnetic Shielding Studies

Given the inability of most space coolers to meet the MIL-STD-461C RE01 requirement on radiated magnetic fields [31], another focus of the JPL cryocooler integration studies has been on achieving compliant systems through the use of magnetic shielding. In support of the AIRS instrument, a number of magnetic shielding studies have been run using various configurations of CO-NETIC AA and Moly Permalloy shields. Tests using a magnetic mock-up of the AIRS cooler, shown in Fig. 12, demonstrated that field reductions on the order of 20 dB could be achieved with external shields. With the final shield design, 0.5-mm (0.020") thick hydroformed Moly Permalloy, the AIRS cooler met the MIL-STD-461C RE01 requirement for radiated magnetic field emissions [8].

Contamination Research

Because growth of the cryogenic load due to surface contamination is a key threat to space cryogenic systems, JPL is actively researching the effects of contamination, both internal and external to the cooler. Ongoing experiments [46] focused on quantifying the effects of gaseous contamination levels internal to pulse tube refrigerators have been recently expanded to include collaborative experiments with UCLA involving using a transparent gas pulse tube to visualize the mechanism of contaminant buildup in an operating cooler.

10 TO 25 K FLIGHT INSTRUMENT CRYO-ENGINEERING

The last of the focuses of JPL's cryocooler program is supporting the development of space instruments that require cryocoolers in the range of 10 to 25 K. Like the higher temperature pulse tube and Stirling based activities, this activity also involves cryogenic instrument design, cryocooler development, cryocooler integration engineering, and cryocooler system testing. Because of the inefficiency of regenerative cryocoolers such as pulse tube and Stirling coolers in this lower temperature range, the major focus of this activity has been the development and application of sorption J-T cryocoolers that use hydrogen as the working fluid [47].

The Sorption Cryocooler Concept

The operation of a sorption cryocooler is based on alternately heating and cooling beds of a sorbent material such as metal hydride powders to pressurize, circulate, and adsorb a gas such as hydrogen in a closed Joule-Thomson refrigeration

cycle. The hydrogen gas is first pressurized to its working pressure (10 MPa, 1500 psi) by heating the sorbent bed to a high temperature ($\sim 450^\circ\text{C}$). After leaving the sorbent bed, the gas is next cooled to around 60 K using passive radiators, often in combination with active Stirling or pulse tube coolers. The hydrogen then flows through a Joule-Thomson (J-T) expansion valve where it cools and partially liquefies at 18 to 25 K. The liquid is collected in a wick contained in the cryogen reservoir, where its evaporation provides cooling to the intended load. Hydrogen vapor leaving the cryogen reservoir is reabsorbed by an unheated hydride sorbent bed, which will later be heated to return the hydrogen to the high-pressure side of the J-T loop.

For sorption coolers providing periodic operation at 10 K, a second step is used after a quantity of liquid hydrogen is collected. At this point the J-T flow is stopped, and solid H_2 at ~ 10 K is produced by vacuum pumping the coldhead reservoir with a special low-pressure sorbent bed. The process is sized to provide sufficient solid hydrogen to absorb the cryogenic heat load over the required operating period. Following the operational period, the cryocooler is recharged by heating the sorbent beds; this drives off the hydrogen and returns it to the high-pressure side of the J-T loop.

Ten Kelvin Brilliant Eyes Sorption Cooler Development

The first development of a flight sorption cryocooler was accomplished by JPL in support of BMDO's Brilliant Eyes mission and is referred to as the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) [48,49]. This novel periodic 10 K sorption cooler concept was invented by Dr. Al Johnson of The Aerospace Corp. in collaboration with Jack Jones of JPL [50-52]. The basic feasibility of the unique 10 K hydrogen/hydride sorption cryocooler was demonstrated at JPL in a series of proof-of-principle experiments in 1991 [53]. Based on this successful demonstration, a comprehensive program was undertaken with industry to reduce the concept to a working prototype and to prove its viability in a space demonstration flight experiment.

The objective of the BETSCE experiment, shown during Shuttle integration in Fig. 13, was to: (1) demonstrate the 10 K sorption cooler technology in a microgravity space environment, (2) advance the enabling technologies and integration techniques by developing an automated, space flightworthy cryosystem, and (3) characterize the spaceflight performance and develop the needed flight database to support flight-cooler development efforts.



Figure 13. BETSCE sorption cooler experiment shown during integration into Space Shuttle Endeavour in May 1996

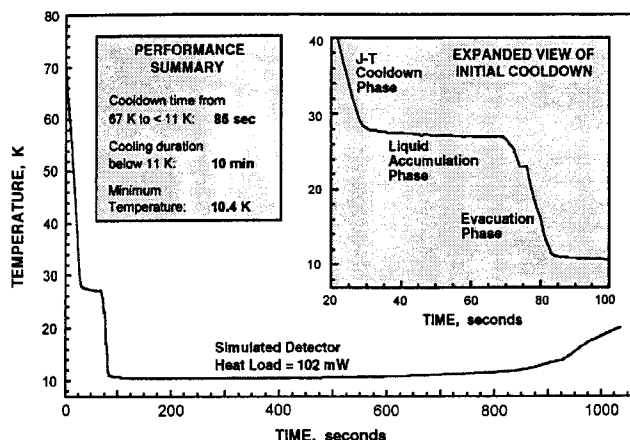


Figure 14. Flight data demonstrating the ability of the BETSCE sorption cooler to provide cooling to 10 K

BETSCE was developed as a teaming between JPL and two key industry partners: Aerojet of Azusa, CA, who provided the hydride sorption compressors [54-56], and APD of Allentown, PA, who provided the cryostat assembly [57]. JPL served as the system designer and project manager, and provided the overall thermal control, structural integration, tank and valve assembly, electronics, and software. Extensive ground testing [58,59] of the complete refrigeration system was carried out over a two year period prior to launch, as well as thorough qualification testing. Figure 14 presents data [49] from the successful flight aboard STS 66 in May of 1996, and demonstrates the ability of the cooler to cool to below 10 K in well under two minutes, and to maintain the temperature over a period of time with a detector heat load of 100 mW.

Supporting the BETSCE flight experiment, JPL also conducted several studies directed at developing the analytical modeling tools to allow the total thermodynamic system to be understood and optimized, and at developing the reliability physics and design understanding of the key issues governing the lifetime and reliability of the system. Extensive analytical models were developed and verified with the ground and flight test data [60,61], and several activities were conducted to verify the long term reliability of the system [62-64]. These reliability physics activities included heater and container-material aging studies, studies to determine the effects of purity and manufacturing techniques on hydride isotherm properties, and studies to establish requirements for preventing migration and compaction of the hydride power. During the design, qualification, and flight of BETSCE, extensive data were developed on the flightworthiness of all of the key elements of the system.

Sorption Cryocoolers for Planck

Building on the successful BETSCE program, JPL is presently working on the development of a hydrogen sorption cryocooler for the Planck mission of the European Space Agency. The objective of the Planck mission is to produce very high resolution mapping of temperature anisotropy in the cosmic microwave background (CMB) radiation. The Planck spacecraft (Fig. 15) is scheduled to be launched around 2007 into a deep space L2 Lagrangian orbit in order to reduce stray infrared radiation from earth and to permit pas-

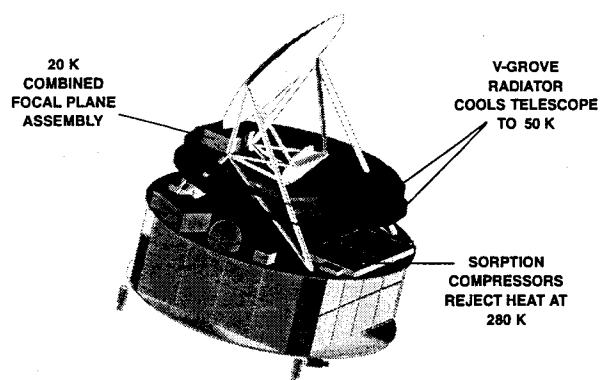


Figure 15. Computer rendition of one of several proposed Planck spacecraft concepts

sive cooling of the telescope and optical system to 50 to 60 K. Two instruments require low temperatures to measure the CMB. The Low Frequency Instrument (LFI) will have an array of tuned radio receivers based on High Electron Mobility Transistors (HEMT) to detect radiation in the range 30-100 GHz. These receivers will be operated at a temperature of about 20 K. The High Frequency Instrument (HFI) will use bolometers operated at 0.1 K for frequencies from 100 GHz to 900 GHz. Redundant hydrogen sorption cryocoolers are proposed to cool the LFI detectors to 18 - 20 K and to precool the RAL 4 K helium J-T that cools the 0.1 K dilution refrigerators in the HFI cooling system [65].

A schematic of the single-stage 20 K sorption cooler proposed for the Planck instruments is presented in Fig. 16. The cooler compressor sorbent beds will contain powder of $\text{LaNi}_{4.75}\text{Sn}_{0.25}$ alloy for the reversible absorption and desorption of hydrogen gas. The compressor is mounted on the Planck spacecraft platform and will be heat-sunk at $T < 280$ K. During operation of the cooler, 6.5 mg/s of compressed refrigerant H_2 , desorbed at 6.7 MPa from a compressor element (sorbent bed) heated to 480 K, is precooled in a tube-in-tube heater exchanger and expanded through the J-T expander orifice to create a gas/liquid refrigerant mixture at

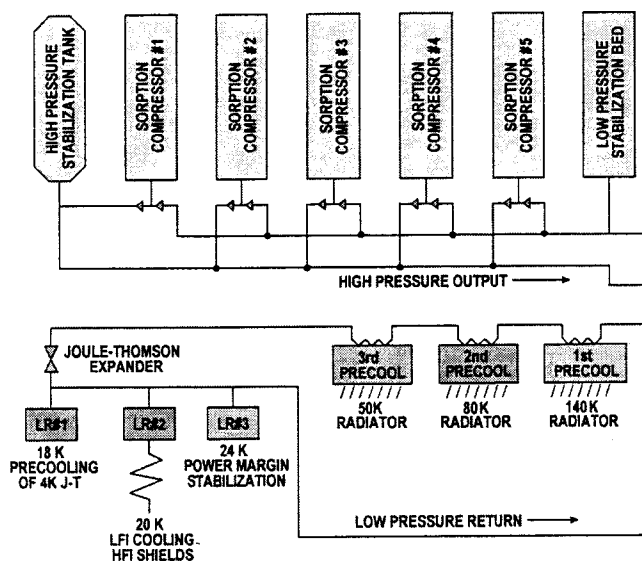


Figure 16. Schematic of a 20 K hydrogen sorption cryocooler being developed for the Planck mission.

0.03 MPa and $T < 18$ K. The liquid hydrogen evaporates as it absorbs heat from the instruments and is warmed as it returns through the tube-in-tube heat exchanger to be absorbed in a cool (i.e., < 270 K) compressor element. The Planck instrument cooler compressor assemblies will each contain five compressor beds. At any point in time one sorbent bed will be heating to pressurize, one hot to desorb gas, one cooling to depressurize, and two beds cold to absorb. Closed-cycle operation is achieved as the compressor beds are switched through each step in this process with the complete heating-cooling cycle taking about 4000 sec. Switching is accomplished by using solid state relays to turn on and turn off electrical heaters embedded in the compressor elements. Gas-gap thermal switches are incorporated into the compressor element design to provide thermal isolation of the bed while in the heating and desorbing phases of operation, and to make the thermal connection to the < 280 K heat sink during the cooling and absorbing phases of operation.

Stable cold-end temperatures are to be achieved through maintaining constant pressure at the J-T expander and the liquid reservoirs. To help accomplish this behavior, a 1.5 liter tank is added to stabilize the high pressure at the compressor outlet and an extra sorbent bed is maintained at the 280 K sink temperature to stabilize the low pressure by simulating an approximately 200-liter plenum volume. A gas manifold with passive check valves, one inlet and one outlet for each compressor element, complete the compressor assembly, and is used to direct the gas flow.

The cold stage includes a contamination filter, a porous plug flow restrictor as the J-T expansion device, and three liquid hydrogen reservoirs. The first reservoir of each cooler is mated to the 4 K helium J-T cooler to provide 0.1 W of precooling at ~ 18 K. The second liquid reservoir is used to provide the rest of the refrigeration required to cool the LFI, shield the HFI, and to intercept parasitics to both instruments, which total approximately 1.3 W at 20 K. The third reservoir is controlled at about 22 K to wick and evaporate any excess liquid refrigerant.

An initial conceptual design for the Planck sorption cooler has been developed and its thermal performance analyzed using transient simulation models. A prototype compressor element has been designed to minimize temperature gradients in the hydride bed and also to incorporate the gas-gap thermal switch. Components for this compressor element are currently in fabrication. Temperature cycling tests will be performed on these prototypes to assess performance and characterize the degradation behavior of the $\text{LaNi}_{4.75}\text{Sn}_{0.25}$ alloy during long-term operation. A breadboard version of the Planck compressor is currently scheduled to be assembled by October 1999 with a complete breadboard cooler to be operating by Spring 2000.

SUMMARY

Over the years the growing demand for long-wavelength infrared imaging instruments for space observational applications has required an increasing commitment to mechanical cryocoolers. To help ensure the success of these cooler commitments, the Jet Propulsion Laboratory implemented an extensive cryocooler program in 1988 directed at assisting in the development of the advanced cryocooler technologies

needed. Over the past 10 years the JPL cryocooler program has played a lead role in the procurement/development of cryocoolers for the AIRS and TES instruments, developed a next-generation pulse tube cryocooler for the IMAS instrument, conducted extensive characterization testing of 22 industry-developed pulse tube and Stirling coolers, developed and flight-tested a wide variety of cryocooler integration technologies, and developed sorption cryocoolers for the 10 to 25 K temperature range.

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